A Novel Approach for the Consolidation of Sand by MICP Single Treatment

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Abstract. Saving natural resources has become increasingly important. In construction, research has been done on alternative methods to replace conventional building materials. One of those novel methods is MICP (microbial induced calcium carbonate precipitation). In this process, calcium carbonate crystals are precipitated with the help of ureolytic bacteria. A cementation solution consisting of urea and calcium salt is used. This precipitation can be used for solidification. In the field of MICP research, there exist multiple publications with several kinds of tests, but no verifiable compressive strength test. However, most researchers are concerned with soil improvement or self-healing methods, to fill cracks in concrete. Similarly, column tests are mainly conducted to investigate the strength. This study presents, a new method of strength assay that uses hardened sand samples of 3 cm edge length. This allows for an accurate compressive strength verification and thus the effect of the biocementation treatment. In addition, this method applies a single treatment method with a novel type of formulation of the MICP components. The results show that a single MICP treatment is sufficient for the consolidation of various sands. Compressive strength of up to 1.8 N/mm² was achieved in the process tests in the uniaxial strength test.

1 Introduction

An increasing amount of research is conducted in the field of biocementation, also known as microbial induced calcium carbonate precipitation (MICP). In the area of Civil Engineering, MICP can lead to novel sustainable applications. The calcium carbonate precipitated is able to bind sand grains together, e.g. to improve the strength and stiffness of soil.

Sporosarcina pasteurii is widely used for this purpose [1–3]. In this process, a cementation solution consisting urea and calcium salt is used. As described by [4, 5], ureolytic bacteria catalyse the hydrolysis of urea, to produce ammonium and carbonate ions (eq. 1). In the presence of calcium ions, carbonate ions precipitate as calcium carbonate (eq. 2).

\[
CO(NH)₂ + 2 \text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + \text{CO}_3^{2-} \quad (1)
\]

\[
\text{CO}_3^{2-} + \text{Ca}^{2+} \rightarrow \text{CaCO}_3 \quad (2)
\]

Several studies already focus on column and injection methods with MICP treatments in various ways to investigate the strength improvement [2, 6–9]. However, these methods also have disadvantages. Due to the common flow-through approach of MICP reagents in these methods, the area of application is limited, to soil consolidation or similar uses. It was found that multiple treatments can cause irregular distribution of CaCO₃ precipitation in the samples [10, 11]. That could lead to an overall reduction in the strength of the column. Testing uniaxial compressive strength is more unreliable because the surface of the columns is often irregular. Alternative strength tests like triaxial compressive strength, tensile strength or surface strength measurements are performed [2, 6, 7].

This study aims to develop a new concept of a single treatment MICP. This concept is transferred to the precipitation method using beakers and sand cubes. Previous studies have produced precipitates by combining cementation solution and culture in flasks [6–8, 12–15]. In this study, a similar method is presented, in order to translate the precipitation effect on the sand samples. Unlike most applications targeting the column test, this study presents a single treatment application with cubic sand samples allowing accurate testing of uniaxial compressive strength.

The single treatment MICP application could offer many advantages in practice. The application would be easier to implement, could save costs and could be adapted flexibly to other fields of application.

2 Materials and methods

2.1 Bacterial culture

In this study, S. pasteurii (DSM33) was used for all MICP experiments. Bacteria culture was provided by the Biotechnology Laboratory of the Department of Engineering and Management. The bacteria were cultivated in a supplemented complex medium, based on the findings by Lapierre et al. [3], allowing for increased

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biomass concentration. The optical density of the culture at wavelength of 600 nm (OD$_{600}$) was found to be at 13.3. The culture was stored at 12 °C before use.

2.2 Cementation solution

CaCl$_2$ was used as a Ca$^{2+}$ source in the cementation solution. The ratio of the two substances was determined by preliminary tests and is approximately 3:4. Preliminary tests and the high solubility led to the decision to use CaCl$_2$ instead of calcium acetate or calcium nitrate as recommended in Van Paassen et al. [5] for soil improvement. The molar concentration for the total volume (bacterial culture and cementation solution) is 1.68 mol/L CaCl$_2$ (molar weight 110.99 g/mol) and 2.22 mol/L urea (molar weight 60.06 g/mol). However, due to the respective dilution of the bacterial culture of three different sets (OD1-3), an individual molar concentration of CaCl$_2$ and Urea results in cementation solution (Table 1). In addition, different pH values resulted due to the varying molar concentrations. To compensate for these variations, the pH of all cementation solutions was adjusted to 8 with HCl.

2.3 Concept of single treatment MICP

The bacterial culture and cementation solution are defined as a total volume for the samples. The total volume consists of a balance of bacterial culture and cementation solution, where the volume of culture used is diluted by the cementation solution. The high OD$_{600}$=13.3 of the culture allows the use of low amount of it in the total volume, which in turn, allows for a higher volume of cementation solution. In order to get a composition with a fixed OD, the exact portions of bacterial culture and cementation solution are calculated. Figure 1 shows this concept.

![Figure 1. Concept of total volume for single treatment MICP.](image)

MICP treated sand samples and precipitation samples were prepared at the same time. Using this approach, the original OD of the culture was diluted by the cementation solution to a total volume with OD1, OD2, and OD3, each. This makes in total 3 sets, each consisting of 20 sand samples and 16 precipitation samples in beakers. The sand and precipitation samples have identical ratios of MICP components, which are given in Table 1. The difference lies in the amount of total volume. The total volume for the precipitation samples in the beaker was upscaled to generate enough mass of CaCO$_3$ for further analyses.

![Figure 2. Precipitated CaCO$_3$ in the beaker (a), filtered CaCO$_3$ (b) and preparation for XRD analysis (c).](image)

### Table 1. Composition of single treatment MICP.

<table>
<thead>
<tr>
<th>series of dilution in total volume</th>
<th>OD 1</th>
<th>OD 2</th>
<th>OD 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria culture (original OD$_{600}$)</td>
<td></td>
<td></td>
<td>13.3</td>
</tr>
<tr>
<td>Concentration in total volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaCl$_2$</td>
<td>1.82 mol/L</td>
<td>1.98 mol/L</td>
<td>2.17 mol/L</td>
</tr>
<tr>
<td>Urea</td>
<td>2.40 mol/L</td>
<td>2.61 mol/L</td>
<td>2.87 mol/L</td>
</tr>
<tr>
<td>MICP Sand samples in mould</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Volume</td>
<td>12.15 mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume Bacteria culture</td>
<td>0.91 mL</td>
<td>1.83 mL</td>
<td>2.74 mL</td>
</tr>
<tr>
<td>Volume cementation solution</td>
<td>11.24 mL</td>
<td>10.32 mL</td>
<td>9.41 mL</td>
</tr>
<tr>
<td>MICP Precipitation samples in beakers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Volume</td>
<td>30.00 mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume Bacteria culture</td>
<td>2.26 mL</td>
<td>4.51 mL</td>
<td>6.77 mL</td>
</tr>
<tr>
<td>Volume cementation solution</td>
<td>27.74 mL</td>
<td>25.49 mL</td>
<td>23.23 mL</td>
</tr>
</tbody>
</table>

*For negative control samples NaCl with same molar concentration was used.

2.4 Preparation of CaCO$_3$ precipitation samples

In order to evaluate the efficiency of the MICP treatment, a CaCO$_3$ precipitate quantification was developed. For this, only cementation solution and culture were combined in beakers (Figure 2 (a)). First, the chemicals for the cementation solution are dissolved in deionised water with the respective molar concentration (Table 1). From this, the required volume of cementation solution was added to beakers. Then the corresponding volume of culture was added to keep the total volume constant at 30 mL. The beakers are stored for the same conditions (40 °C) as the sand samples.
The experiments were carried out at room temperature. Different storage periods were chosen to study the MICP process. Thus, three CaCO₃ precipitation samples each from beakers were filtered after 1, 3, 7, 10, and 14 days. Furthermore, negative control samples were prepared for each set as a control. These consist of cementation solution with NaCl instead of CaCl₂ to avoid precipitation. After filtering, the precipitate was dried at RT and the amount of precipitated CaCO₃ was weighed. By comparing the results with the calculated values, a precipitation rate can be determined. It is assumed that only insoluble substances such as the CaCO₃ which is formed, remain in the filter. Filter papers with 4 - 7 µm particle retention were used (Figure 2 (b)).

To examine the consumption of the Ca²⁺ ions from the cementation solution, a complexometric Na₂-EDTA (disodium Ethylenediaminetetraacetic acid) titration with the filtrate was performed. In addition, for the examination of by-products, rapid tests (QUANTOFIX® by Macherey-Nagel) were used, which measure the content of ammonium ions. This method allows determining the pH value, the reaction rate, the CaCO₃ conversion and the quantity and quality of the precipitation to analyse the precipitation process. The density of the precipitate was measured with a gas (He) pycnometer. X-ray diffraction analysis (XRD) was performed on the samples to analyse the phase composition of the precipitated CaCO₃. A PANalytical Aeris diffractometer (Malvern Panalytical) with CuKα1 was used. The samples were scanned in the 5 – 70 °2θ range, with a step size of 0.02° and a step time of 25.5 s. For this purpose, the samples were ground with an XRD Mill (McCrone) with the addition of a ZnO standard and filtered again with cellulose nitrate membrane filter (Figure 2 (c)). This allows the determination of amorphous content of the samples. XRD was evaluated by element restriction determined after XRF Element analysis (X-ray fluorescence) of the precipitate. For quantitative results, a Rietveld analysis was carried out. CaCO₃ formation also was confirmed by scanning electron microscopy (SEM).

This CaCO₃ precipitation method in beakers was used in advance, on the one hand, to pre-determine the optimum concentrations and ratios of cementation solution and, on the other hand, to evaluate the MICP treatment of the sand samples. It is assumed that the results of the precipitation samples in the beaker can be used to infer the MICP performance of the sand samples.

2.5 Preparation of MICP treated sand samples

In this study, two different types of fine sand were used: quartz and calcareous sands. To keep the conditions consistent, a total volume of 12.15 mL (cementation solution and bacterial culture) was defined. This corresponds to the pore space of the sand sample with minimal supersaturation. The particle size used was 0 – 1 mm each. For a sample of quartz sand, 40 g of sand was used, and 45 g for the calcareous sand type. The sand samples are chosen to be cubic with an edge length of 3 cm. This form allows for optimal testing of uniaxial compressive strength. In addition, a smooth surface of the samples is achieved. The mould was made using a 3D printer PLA filament (polylactic acid). For better demoulding, the side surfaces were covered with vinyl foil. A mould with a sand sample is shown in Figure 3.

First, the sand for each sample was mixed with the respective amount of cementation solution. Afterwards, the culture was added. In the end, the resulting paste was filled into the mould under slight pressure. The exact composition of the cementation solution and bacterial culture for the samples are given in Table 1.

After the sand samples were prepared, they were stored for 24 h at room temperature. Preliminary test results showed that the precipitation process was completed within 3 - 4 hours. The samples were then stored in a climate cabinet at 40 °C and 10% relative humidity for 13 days to accelerate the drying of the samples. The weight of the samples was measured before and after drying. The uniaxial compressive strength of the samples was tested on day 14. For each OD dilution, 8 samples with MICP treatment and 2 negative control samples (NaCl instead of CaCl₂ in cementation solution) were prepared.

For the compressive strength testing, the sand samples were placed between two steel blocks (Figure 4 (b)). This was done to achieve accurate force application without lateral interference. A ZwickRoell testing machine with a pre-load of 1 N and a speed of 7 mm/min was used.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** MICP treated sand sample in mould with sketch of the 3D printed mould.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** MICP treated sand sample after demoulding (a), during uniaxial compressive strength test (b), after testing (c) and schematic sketch (d).

The fracture characteristics of the samples show a typical hourglass shape after testing (Figure 4 (c)). This indicates
a homogeneous force application on the surface of the sample.

3 Results

3.1 Precipitation sample results

To observe any changes in CaCO$_3$ formation and the precipitation quantity over time, triplicates of each precipitate sample were filtered after 1, 3, 7, 10, and 14 days. Average value of each triplicate is calculated for each filter day. The results of the precipitation rate are presented in Figure 5.

It is observed that samples of OD3 almost have precipitated the maximum amount of CaCO$_3$ possible in theory after the first day. The precipitation rate remains nearly constant at about 97.8 - 99.3% over the tested time duration. In contrast, the samples with OD1 reach only 73.1% of the possible precipitation after 24 hours and increase to 93.8% by day 14. The samples with OD2 are in the middle range between OD1 and OD3 and increase from 81.8% (24 h) to 96.3% (14 days).

From the results of the Ca$^{2+}$ ion titration can be noticed that they closely coincide with the measured amount of converted CaCO$_3$. If the precipitation rate is compared with the results of the remaining Ca$^{2+}$ ions, a conclusive behaviour can be observed. The more precipitation is left after filtering, the less free Ca$^{2+}$ ions are left in the solution. Also, the results of pH values and ammonium concentrations as a function of time were measured on the same samples (data not shown). While the NH$_4^+$ concentration increases over time, the pH of the solution decreases at the same time. Regardless of the OD dilution, this effect seems to occur in all samples.

According to the XRD analysis of the precipitate, the respective percentage distribution of the CaCO$_3$ polymorphs calcite, vaterite and the amorphous content within a measured CaCO$_3$ sample were identified. The results are given in Figure 6. In general, it is noticed that the calcite content of the precipitate increases over time while the vaterite and amorphous content decreases at the same time. This effect is more pronounced in the precipitate with OD1 dilution. The calcite after 14 days reaches 89.3% based on 100% of the measured sample while the vaterite is only 5.3%. In contrast, samples with OD3 achieve only 56.2% calcite and the vaterite remains with over 34.4%. In the samples with OD2, a strong increase from day 3 to day 7 can be observed. The highest calcite content is reached on day 10, which, however, seems to decrease again on day 14.

Figure 6. Percentage distribution of calcite, vaterite and the amorphous content.

SEM images confirm this effect of transformation of the CaCO$_3$ polymorphs present. Figure 8 (a-c) shows how calcite is formed from vaterite structures. Figure 8 (d-e) shows images of precipitates with OD3. There are many bacteria traces in the precipitate, which indicate the high number of encapsulated cells. Whereas in image Figure 8 (f) with OD1, no bacterial residues are found.

3.2 Results of sand samples

Uniaxial compressive strength was tested on sand samples treated with MICP, including negative control samples with NaCl instead of CaCl$_2$. The results are shown in Figure 7. The average value of the strength of 8 samples was calculated for each OD dilution series and sand type. However, one sample of the quartz sand with OD1 and OD3 was damaged during demoulding.

Figure 7. Results of uniaxial compressive strength of MICP treated sand samples and negative control samples after 14 days. The error bars depict the standard deviation.

The results show that the calcareous sand samples are approximately in a similar range independent of the OD
dilution. The compressive strength is between 1.348 N/mm² and 1.558 N/mm². However, the values of the OD2 series show a higher standard deviation compared to the others. The highest average value of compressive strength of 1.815 N/mm² is found in the OD1 series of quartz sand samples. In contrast, OD2 and OD3 are notably lower at 0.8 N/mm². Additionally the standard deviation is more pronounced in these two series. It can be observed that the corresponding control samples achieve higher compressive strengths with calcareous sand compared to quartz sand.

SEM images (Figure 8 (g-i)) of the treated sand samples show how the precipitated calcite crystals cover the quartz sand grains and form a compound. This is clearly shown in Figure 8 (h) on which a remaining calcite structure can be seen in which a grain of sand must have been placed before.

4 Discussion

4.1 Transferability of results from precipitation samples to sand samples

A number of studies have performed similar experiments with precipitates in tubes to investigate the quality and quantity of the CaCO₃ formed [6–8, 12–15]. It is assumed that the precipitation in the beaker will behave similarly to the treated sand samples and results could be derived from this. The formation of CaCO₃ crystals and their content in the sand samples is important for the success of biocementation [7, 16]. In Konstantinou et al. [8], the results of precipitation in the flask corresponded to the CaCO₃ content of the sand samples. Cheng et al. [15] also used the results of the precipitation samples to find the optimum ZL and transferred them to sand samples. However, in Badiee et al. [6] the precipitation rate in the
sand samples was found to be lower than in the tubes. Therefore, they conclude that a low biocementation effect occurred in the sand columns, which was due to other influencing factors. Due to the method using flow-through sand samples with multiple injections of cementation solution, there may be a decrease in CaCO$_3$ content in the soil [11]. This should not be the case with the samples in this study as it is a single treatment. According to [17, 18], the formation of CaCO$_3$ depends also on the relative density of the soil. Also, Omoregie et al. [7] could not find any correlation between CaCO$_3$ content and the surface strength of the soil samples. Similar result was obtained by Sharma et al. [9], which could not establish a correlation between high CaCO$_3$ content and strength. However, an increase in CaCO$_3$ content and strength by increasing cementation solution concentration was observed in Omoregie et al. [7].

4.2 Effect of the cementation solution on MICP

The concentration of the cementation solution plays an important role in the formation of CaCO$_3$ by MICP [19]. Several studies [4, 7, 20] have suggested that a high concentration of CaCl$_2$ and urea, as it is also used in this study, positively affects the precipitation process of MICP. In Lee et al. [20], it was found that the highest concentration of 1.5 mol/L urea and 0.75 mol/L CaCl$_2$ in the cementation solution results in a high-water resistance than lower concentrations. Omoregie et al. [7] were able to increase the CaCO$_3$ content by increasing the cementation solution. However, Carmona et al. [12] could prove with their test tube method that the precipitated CaCO$_3$ can also decrease with increasing concentration of cementation solution and thus increase the strength of the stabilized soil. This has further been confirmed by Cheng et al. [15]. A high concentration in the cementation solution causes a high pH value. To avoid this, in the present study, the pH was previously adjusted to 8 to create equal conditions. Even though there are differences in the precipitation rate and crystal formation of the precipitated CaCO$_3$, all precipitation samples precipitated more than 90% CaCO$_3$ after 14 days, which corresponds to Lee et al. [20]. Thus, it seems that despite the high concentration of the cementation solution chosen, it was finally converted to CaCO$_3$.

The results of pH and NH$_4^{+}$ content show an opposite trend. The pH of the samples in beakers increased after a short time and then fell into neutral (pH≈7) as soon as CaCO$_3$ precipitated. This result was observed in Omoregie et al. [7] as well. However, the concentration of NH$_4^{+}$ ions increased continuously. These results are consistent with other studies [5, 7, 10, 13, 15]. Hydrolysis of urea produces ammonium or ammonia so the concentration of urea in the cementation solution also affects the pH [5, 7, 10, 13, 15]. Similar to Stocks-Fischer et al. [13], Ca$^{2+}$ titrations were obtained supporting this hypothesis. It indicates that the conversion of cementation solution components can be verified by measuring ammonium/ammonia and Ca$^{2+}$ titration during the precipitation process [15]. However, a low pH also could result in less ammonia concentration and can cause a slower precipitation rate [14].

Deposits could be found on the surfaces of the sand samples in this study. As described in Omoregie et al. [7], the high concentration of the cementation solution could form salt deposits. When CaCl$_2$ is used in cementation solution, NH$_4$Cl is formed as by-product that can precipitate [4, 5, 13]. The EDX results confirm that NH$_4$Cl is present in the sand samples. In the quartz sand samples, however, it could be detected almost exclusively at the surface. Whereas in calcareous sand samples NH$_4$Cl was also found inside.

4.3 Effect of OD Dilution on CaCO$_3$ formation and compressive strength

The results of the precipitation samples suggest that the use of a high number of cells leads to a faster precipitation rate. Omoregie et al. [7] could observe a rapid precipitation rate within 1 - 4 hours. In Cheng et al. [14], it was reported that the precipitation process started within seconds at a high concentration of cementation solution. They concluded that the lower the pH the slower the rate of precipitation. At high number of cells, no correlation between pH and precipitation rate could be found. In this study, similar results can be observed in the precipitation samples. The samples with a low number of cells (OD1) where a low pH was measured show a slower precipitation rate over time. Only after 14 days, more than 90% of the CaCO$_3$ seems to have precipitated. Whereas in samples with a high number of cells (OD3) almost 100% of the CaCO$_3$ has already precipitated after 24 h. [13, 21] support the idea that a high concentration of cells is effective in biocementation. Lee et al. [20], however, could not detect any significant influence of the number of cells. High OD$_{600}$ can result in higher compressive strength and larger CaCO$_3$ particles due to higher urease activity and more nucleation sites [21]. Konstantinou et al. [8] established a correlation between OD$_{600}$ and urease activity on precipitation rate. Low OD$_{600}$ led to higher biocementation effect of the sand samples, although this effect was reversed when using bacterial culture with high urease activity. With decreasing urease activity, the crystals became larger and formed clusters that formed more effective bridges between particles.

Cheng et al. [22] report about large cluster formation at low urease activity, which increased the unconfined compressive strength as well. Wang et al. [23] found, that at low OD$_{600}$ of 0.2, crystals formed slowly but larger. At high OD$_{600}$ of 3, the amount of precipitation increased but more unstable forms of CaCO$_3$ were found. This could be the reason why the quartz sand samples with OD1 show higher strength than those with higher OD3. For the calcareous sand samples, the OD dilution does not seem to have any influence on compressive strength. All three series are in a similar range. The lower OD thus leads to a slower precipitation rate and the CaCO$_3$ crystals form more effective bridges between the sand particles (Figure 8 (g-i)). This conclusion is also supported by the XRD
results. After 14 days with OD1 the highest calcite content is found, whereas calcite and vaterite show rather balanced proportions at OD3 (Figure 5).

Wang et al. [23] explain the relationship between phase transformation and the initial supersaturation state. This depends on both: urea hydrolysis and the precipitation process. The high OD could have affected the rate of ureolysis, which in turn affects the formation of CaCO$_3$ phases. At low OD, CO$_3^{2-}$ ions are formed slowly and calcite is more likely to be formed depending on the concentration. Thus, transformations of ACC-Vaterite-Aragonite- Calcite can occur. Calcite is the final product. However, other factors such as contaminants, bacterial culture, or nucleation sites can also influence the formation of CaCO$_3$ polymorphs [24, 25]. The formation of different polymorphs of CaCO$_3$ as seen in Figure 8. (a-c) is quite plausible and has already been reported in other studies [2, 24, 26]. Various polymorphs of CaCO$_3$ were also found in Zhao et al. [2], with mainly aragonite precipitating. Vaterite [26] or Calcite [12, 13, 19] were found to be a major component of the precipitate. However, there is usually a composite of calcite and vaterite [6, 7], as is also the case in this study. In Cheng et al. [15] similar formations with encapsulated cells were reported at high OD$_{600}$ as also shown in this study (Figure 8 (d-e). In Figure 8. (g-i) sand samples with OD1 a strong calcite matrix can be seen connecting the sand grains as also was the case in [2, 8, 10, 14]. Compressive strength of MICP treated samples depends on many factors. In a direct comparison between the two types of sand, it is observed that in the case of samples made of quartz sand the OD appears to influence the compressive strength. The MICP treated calcareous sand samples achieve compressive strengths of about 1.3-1.5 N/mm$^2$ regardless of OD. The negative control samples with OD1 and OD2 of calcareous sand also achieve some consolidation between 0.3-0.5 N/mm$^2$ without precipitated CaCO$_3$. This was not the case with quartz sand. This suggests that the cause is the sand type and not the MICP process, which needs further investigation. In most studies, fine quartz sand is used for the MICP treatment [2, 5, 6, 10, 11]. However, Xiao et al. [17] investigated the impact of relative density on the cyclic behaviour of bio cemented calcareous sand columns. The dominant method, however, is testing compressive strength on MICP treated sand columns [2, 6, 9, 10, 14]. Badiee et al. [6] were able to achieve an unconfined compressive strength of 6.7 N/mm$^2$ in bio-cemented columns. However, in the present study, the highest compressive strength (average value) of 1.8 N/mm$^2$ was achieved with OD1 and quartz sand by MICP single treatment comparable with results from Zhao et al. [2] at high urease activity. Also, Sharma et al. [9] and Wen et al. [16] achieve similar strengths with samples of high CaCO$_3$ content. Some studies [9, 10, 14, 16] found a correlation between CaCO$_3$ content and compressive strength. In the present study, a similar effect could be observed only with the samples of quartz sand based on the calcite content of CaCO$_3$ shown in Figure 9. It can be observed that the compressive strength reduces due to decreasing calcite and increasing vaterite and amorphous content.

![Figure 9. Compressive strength of the quartz sand samples as a dependence of the CaCO$_3$ crystal morphology of the precipitation samples.](image)

5 Conclusion

The results of the precipitation samples in the beaker agree with the SEM images of the sand samples. Therefore, it can be assumed that the findings can be transferred. In order to monitor the parameters and for comparison, it is reasonable to prepare precipitates for each sand sample at the same conditions simultaneously in the beaker. Additionally, it is presented that the concept of cubic sand samples with MICP single treatment can achieve quite similar compressive strengths as sand columns that have been flushed or injected with bacteria and cementation solution. Due to the mortar-like preparation and the single application, this method could be an alternative to common column methods and lead the way to more application possibilities.

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